LLNL-CONF-694399

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B. S. Victor, C. T. Holcomb, S. L. Allen, W. H. Meyer, M. A. Makowski, A. Thorman

June 7, 2016

High Temperature Plasma Diagnostics
Madison, WI, United States
June 5, 2016 through June 9, 2016

Asymmetries in the motional Stark effect emission

B. S. Victor,[1, a] C. T. Holcomb,[1] S. L. Allen,[1] W. H. Meyer,[1] M. A. Makowski,[1] and A. Thorman[2]

[1] *Lawrence Livermore National Laboratory*

[2] *Australia National University*

(Dated: 26 May 2016)

Spectrometer measurements and filter upgrades to a motional Stark effect (MSE) polarimeter measuring the outer half radius of the DIII-D tokamak helped to identify asymmetries in the polarization angle of Stark-split emission. The measured polarization angle of the π components differ and are not orthogonal to the σ component. These differences persist over a range of densities, and with low levels of background light. It is suggested that the difference in the polarization angle between components is from a change in the ellipticity of the emitted light across the Stark components coupled with imperfect polarization preservation from an in-vessel mirror.

PACS numbers: 52.55.Fa, 52.70.Kz

[a] Electronic mail: victorb@fusion.gat.com

I. INTRODUCTION

The motional Stark effect (MSE) diagnostic measures the polarization angle of Doppler-shifted, Stark-split D_α emission from neutral beam atoms[1,2]. The Stark effect arises from a large effective electric field, $\vec{v} \times \vec{B}$, experienced by the neutral atoms, where $\vec{v}$ is the beam velocity and $\vec{B}$ is the local magnetic field in the plasma. There are 9 bright Stark lines split into 3 groups, a central σ component and two π components, Fig. 1. When viewed in a direction transverse to the electric field, the polarization angle of the π components is parallel to $\vec{E}$ and the polarization angle of the σ component is perpendicular to $\vec{E}$. Viewed parallel to $\vec{E}$ the light is unpolarized. The direction of the electric field can be found from the polarization angle of either component. However potential complications arise due to background polarized light[3] and non-statistically populated excited states[4]. In addition the effects of the local electric field in the plasma need to be taken into account to accurately measure the pitch angle of the magnetic field[5,6].

The DIII-D MSE polarimeters are constructed with two photo-elastic modulators (PEM) that oscillate the polarization angle of the light at 20 and 23 kHz[7]. Lock-in amplifiers at twice the PEM drive frequency measure the direction of the linearly polarized light[8]. Theoretically, allowing some π light through the bandpass only affects the signal-to-noise ratio[2], but in practice π light has been shown to change the measured polarization angle[9].

The edge MSE polarimeter on DIII-D[8] was designed to give overlapping coverage with the original ('tangential') DIII-D[7] MSE system in the outer-half radius of the plasma, including high resolution in the pedestal region. One difference between the edge system and the tangential system is the use of an in-vessel mirror[8]. Design calculations for angles of incidence between 48 and 68 degrees indicate s and p reflection amplitudes are equal to within 1%, with the phase shift between the two polarizations being held to less than 15°.

To improve the measurements of this system and better constrain the pitch angle in the outer-half radius of the plasma, the Stark emission has been measured with a 0.75 m Czerny-Turner spectrometer, and the filter and detectors have been replaced on each channel. The Doppler shift of each channel has been measured with the spectrometer to ensure that the correct filter is used for each channel. Each of the filters has been replaced with new bandpass filters from Alluxa with a FWHM of 0.3 nm and >90% transmission at the central wavelength. Figure 1 shows the spectrum with and without the bandpass filter.

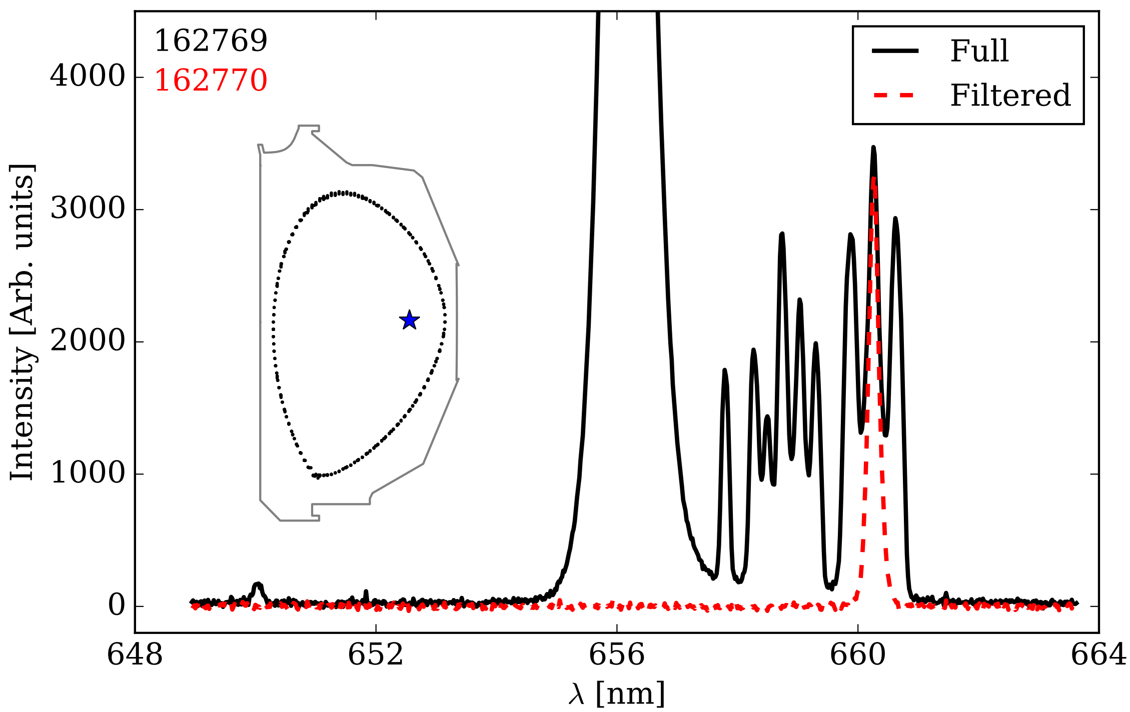

FIG. 1. The Stark-split emission and neighboring lines from channel 13 (R = 2.04 m, inset) are shown integrated over a full shot (solid black). The three rightmost lines are the Stark-split emission from the full-energy neutral particles. The bandpass filter isolates the σ component (dashed red).

II. ASYMMETRIES IN THE POLARIZATION ANGLE OF THE STARK-SPLIT EMISSION

Spectrometer measurements revealed asymmetries in the Stark-split emission, Fig. 2. The sampling rate of the spectrometer measurement is 100 Hz, and Fig. 2 shows the sum of the spectra over a two second period of the shot when the polarization angle is constant for each shot to within 1°. Measuring the spectra with only one PEM on revealed differences in the intensity of the π components. The amplitude of the DC component of polarized light in a two PEM system is

$$I\left(\omega=0\right) \propto 1+\frac{\cos 2\chi}{\sqrt{2}}\left(\cos 2\gamma J_0\left(A_2\right)+\sin 2\gamma J_0\left(A_1\right)\right) \tag{1}$$

where γ is the polarization angle, χ is the ellipticity, J_0 is the Bessel function of the first kind, A_1 and A_2 are the retardation amplitudes of the respective PEMs. The retardation amplitudes are set to be halfwave at the PEM controller design wavelength (≈6600 Å) so there is less than 0.2% difference in the retardation amplitude over the Stark-split emission.

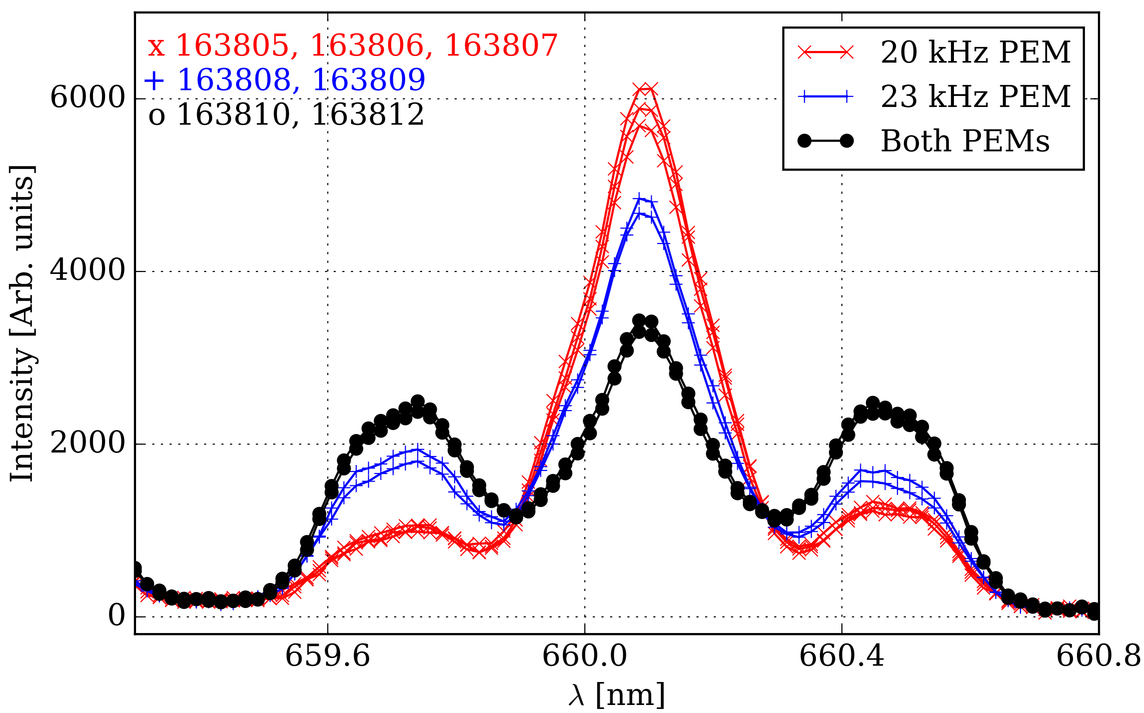

FIG. 2. Two second integration of the Stark-split emission of channel 14 (R = 2.09 m): both PEMs on (black o), 20 kHz PEM on (red x), 23 kHz PEM on (blue +).

Asymmetries in the measured electric field angle are also apparent from the ratio of the second harmonic components. Fig. 3 shows the electric field angle measured by channels 14 through 16 for two similar shots. (The electric field angle is parallel to the polarization angle of the π light and perpendicular to the polarization angle of the σ light.) The electric field angle is calculated from the amplitude of the PEM second harmonic components output from a lock-in amplifier[10]. Channels 14 and 16 measure the polarization angle of the σ light. For the first shot channel 15 measures the polarization angle of the higher wavelength π components (π^+), and for the second shot channel 15 measures the polarization angle of the lower wavelength π components (π^-). The polarization angle measurements from the tangential MSE system for these shots indicate that the polarization angle varies linearly between channels 14 and 16.

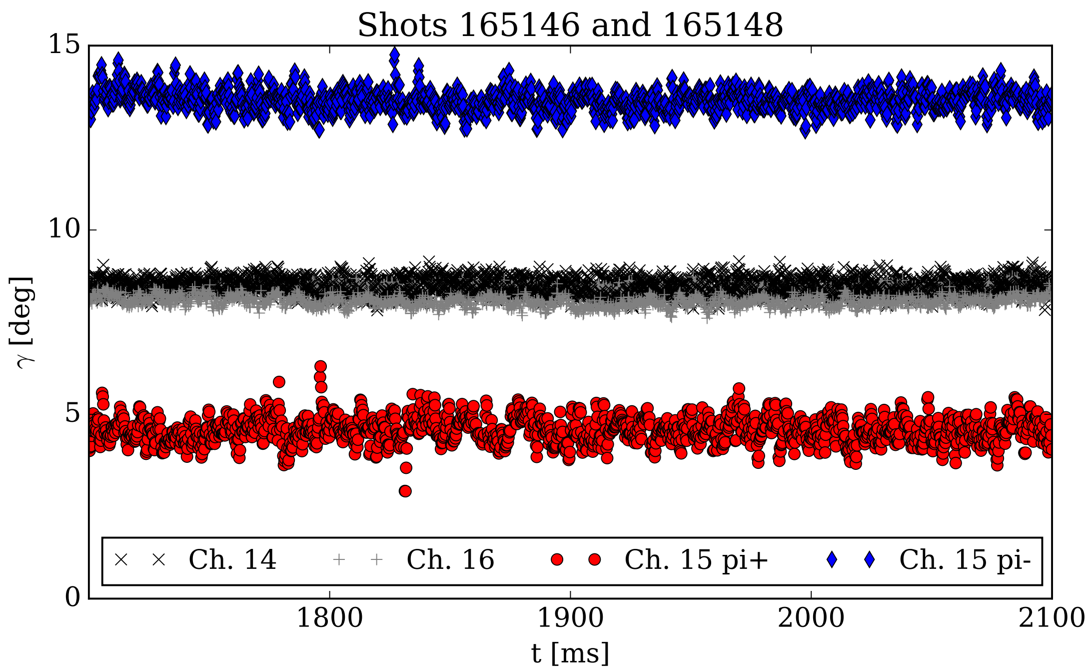

FIG. 3. The angle of the electric field measured with different Stark components for two similar shots. Channels 14 (black x) and 16 (grey +) measure σ light, and channel 15 measures π^+ (red $\circ$) and π^- (blue $\diamond$) light respectively.

A. Absence of background light

Background polarized light can affect the measured polarization angle[3]. Comparing the spectra with and without the neutral beam on shows low levels of background light in the edge MSE system on DIII-D. Each sample from one shot shown in Fig. 2 is plotted in Fig. 4. When the observed neutral beam is on, the full, half, and third energy Stark-split emission are visible. The third energy Stark-split emission overlaps a CII line and the half energy Stark-split emission. In addition the thermal D_α line broadens with the beam on.

B. Density dependence

Non-statistically populated excited states in low density plasmas have been used to explain discrepancies in MSE polarization angle measurements[4]. The difference in polarization angle between the σ and π components versus density is plotted in Fig. 5. $\Delta\gamma$ is calculated by taking the difference between the polarization angle of the π^+ light measured by channel

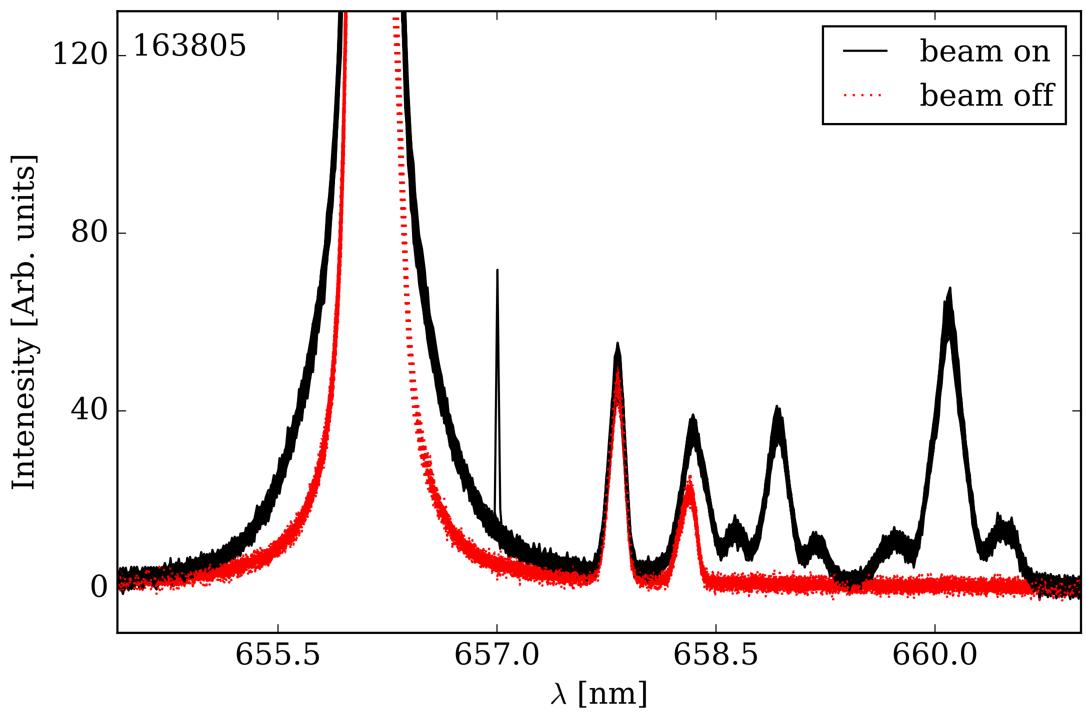

FIG. 4. Each time slice from the time range that makes up the data for shot 163805 in Fig. 2. Times with the beam on are shown in black and times with the beam off are shown in red.

15 and the average polarization angle of the σ light measured by channels 14 and 16. The density plotted is the line-averaged density from a vertical interferometer chord with a mid-plane radius of 2.10 m. The difference in the polarization angle between the σ and π light is expected to be $90°$[2].

III. DISCUSSION

The new filters and detectors helped to improve the signal-to-noise ratio for the edge channels, but did not improve the channel resolution to the desired accuracy in the polarization angle of 0.1°, the level necessary to resolve the current density profile in the outer-half radius of the plasma. The source of the systematic error appears to stem from the non-orthogonal polarization angles of the σ and π components.

Ref. 4 states that statistical population distribution is a reasonable approximation for beam into plasma shots at densities above 5×10^{19} m^{-3}. The density range in Fig. 5 spans

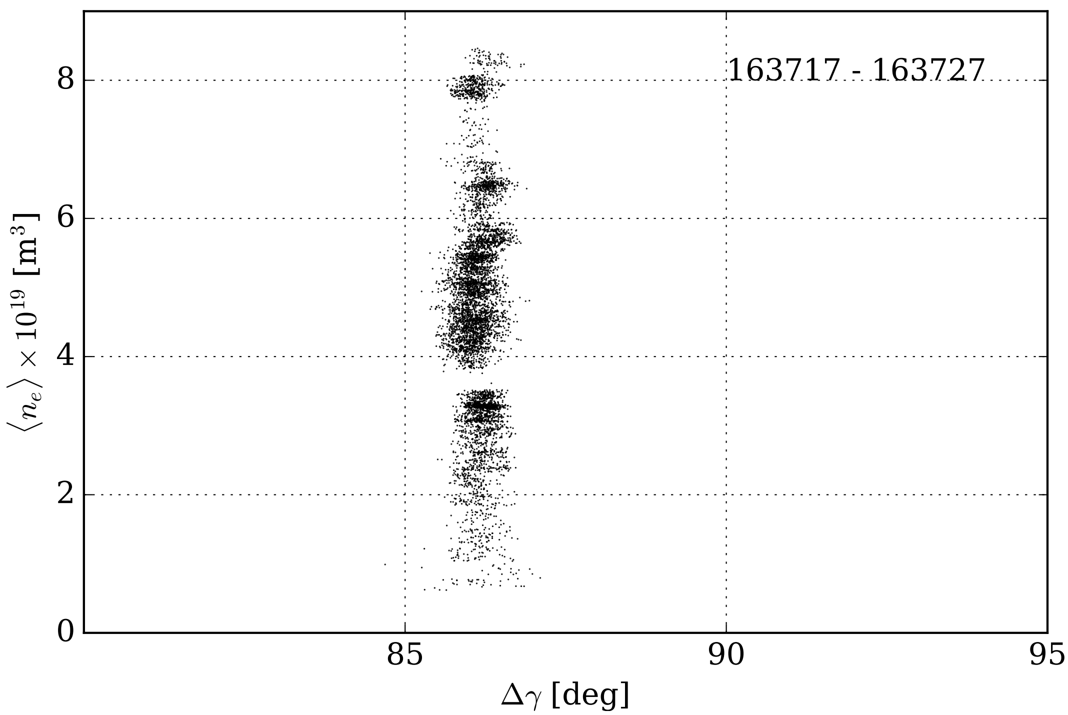

FIG. 5. The difference in the polarization angle between π light measured on channel 15 (R = 2.13 m), and the average of σ light measured on channels 14 and 16 versus line-averaged density for a vertical interferometer chord at midplane R = 2.10 m for 10 shots.

well above and below this number, thus the differences between the σ and π polarization angles does not appear to be accounted for by non-statistically populated excited states. In addition, the background light level is an insignificant portion of the signal in the region of the Stark-split emission, Fig. 4, indicating that background polarized light is not responsible for the asymmetries seen in the Stark-split emission.

The π lines have a large difference in the measured polarization angles only in the system with a mirror. A phase shift between the s and p polarization components by the edge mirror is capable of converting linearly to elliptically polarized light and vice versa. π lines from atomic models of the combined Stark-Zeeman effect have opposite circularity[4]. Thus a change in the handedness between the π lines, as predicted by the Stark-Zeeman effect, coupled with a non-ideal mirror would explain the differences in polarization angle measured between the π components.

The edge calibration is performed with linearly polarized light and conversion from linearly to elliptically polarized light does not change the polarization angle measurements because the ratio of the second harmonic components is not affected by the presence of elliptically polarized light. However, the conversion of elliptically to linearly polarized light by the mirror would have an effect on the measured polarization angle as it would appear to the polarimeter as linearly polarized light. The problem is compounded in the edge of the plasma where the magnetic field strength is the lowest, leading to lower separation between σ and π components.

IV. CONCLUSION

In conclusion, the filters and detectors in the edge MSE system on DIII-D have been upgraded. The new hardware and spectrometer measurements have helped to identify asymmetries in the Stark-split emission and apparent differences in the polarization angle of the two π components. Differences in the polarization angle of the π light mean that the inclusion of any π light into the bandpass will cause measurement errors. Large polarization angle differences in the π components arise over a range of densities, without significant background light, and in systems with a mirror. A change in the circularity of the π components coupled with a non-ideal mirror explains the difference in the measured polarization angles. The best solution to overcome this problem is to construct MSE polarimeters without an in-vessel mirror if at all possible.

ACKNOWLEDGMENTS

This material is based upon work supported by the U.S. Department of Energy Office of Science, Office of Fusion Energy Sciences under Award Number DE-AC52-07NA27344, DE-FC02-04ER54698, and DE-FG02-04ER54761.

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